Experimental search for radiative decays of the pentaquark baryon $\Theta^+(1540)$

DIANA Collaboration

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Abstract

The data on the reactions $K^+\mathrm{Xe} \to K^0\gamma X$ and $K^+\mathrm{Xe} \to K^+\gamma X$, obtained with the bubble chamber DIANA, have been analyzed for possible radiative decays of the $\Theta^+(1540)$ baryon: $\Theta^+ \to K^0 p\gamma$ and $\Theta^+ \to K^+ n\gamma$. No signals have been observed, and we derive the upper limits $\Gamma(\Theta^+ \to K^0 p\gamma)/\Gamma(\Theta^+ \to K^0 p) < 0.032$ and $\Gamma(\Theta^+ \to K^+ n\gamma)/\Gamma(\Theta^+ \to K^+ n) < 0.041$ which, using our previous measurement of $\Gamma(\Theta^+ \to KN)= (0.39\pm0.10)$ MeV, translate to $\Gamma(\Theta^+ \to K^0 p\gamma) < 8$ keV and $\Gamma(\Theta^+ \to K^+ n\gamma)$ < 11 keV at 90% confidence level. We have also measured the cross sections of K^+-induced reactions involving emission of a neutral pion: $\sigma(K^+ n \to K^0 p\pi^0) = (68 \pm 18)$ μb and $\sigma(K^+ N \to K^+ N\pi^0) = (30 \pm 8)$ μb for incident K^+ momentum of 640 MeV.

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Possible existence of multiquark hadrons, and pentaquark baryons in particular, has been discussed for many years [1]. Fairly definite predictions for the antidecuplet of light pentaquark baryons with spin–parity $1/2^+$ have been formulated by Diakonov, Petrov, and Polyakov in the framework of the chiral quark–soliton model [2]. In particular, they predicted $m \simeq 1530$ MeV and $\Gamma < 15$ MeV for the mass and width of the explicitly exotic baryon with $S = +1$ and $I = 0$, the $\Theta^+(uudd\bar{s})$ that should decay to the nK^+ and pK^0 final states. Narrow peaks near 1540 MeV in the nK^+ and pK^0 mass spectra were initially detected in low-energy photoproduction by LEPS [3] and in the charge-exchange reaction $K^+n \to pK^0$ by DIANA [4]. Other searches for the Θ^+ baryon in different reactions and experimental conditions yielded positive evidence as well as null results casting doubt on its existence, see the review papers [5] and [6]. However, both LEPS and DIANA were able to confirm their initial observations [7, 8, 9].

Using the unique properties of the charge-exchange reaction that forms Θ^+ baryons in the s-channel, DIANA reported a direct measurement of the Θ^+ intrinsic width: $\Gamma = 0.39 \pm 0.10$ MeV [8, 9]. The extreme smallness of the Θ^+ width, as compared with well known baryons, indicates a strong dynamical suppression of the "fall-apart" mechanism of Θ^+ decays to pK^0 and nK^+. This does not necessarily imply that radiative decays to γpK^0 and γnK^+ should be equally suppressed, so that the relative probability of radiative decay may prove to be higher for the Θ^+ baryon than for ordinary hadrons. Indeed, partial widths of the radiative decays $\Theta^+ \to K^0p\gamma$ and $\Theta^+ \to K^+n\gamma$ have been computed in [10] as $\Gamma(\Theta^+ \to K^+n\gamma) = 34$–$41$ keV and $\Gamma(\Theta^+ \to K^0p\gamma) = 0.25{\times}\Gamma(\Theta^+ \to K^+n\gamma)$, so that $\Gamma(\Theta^+ \to K^+n\gamma)/\Gamma(\Theta^+ \to K^+n) \simeq 0.15$ if $\Gamma(\Theta^+ \to K^+n) = 0.5{\times}\Gamma(\Theta^+ \to KN)$ and the measured value of $\Gamma(\Theta^+ \to KN)$ [9] is substituted. On the other hand, the Θ^+ radiative widths predicted in [11, 12] using different assumptions are smaller than in [10] by nearly two orders of magnitude[1]. Anyway, the simple arguments brought above and the prediction [10] for $\Gamma(\Theta^+ \to KN\gamma)$ provide adequate motivation for a search for radiative decays $\Theta^+ \to K^0p\gamma$ and $\Theta^+ \to K^+n\gamma$ in the DIANA experiment. The results of the search are reported in this paper.

The non-magnetic bubble chamber DIANA [13] was filled with liquid Xenon and exposed to a separated K^+ beam with incident momentum of 850 MeV at the proton synchrotron at ITEP, Moscow. The fiducial volume of the chamber was $700 \times 700 \times 1400$ mm^3, and the density and radiation length of the fill were 2.2 g/cm^3 and 3.2 cm,

[1] An important conclusion reached in [12] was that the parity of the Θ^+ baryon can be determined from the shape of the γ energy spectrum.

respectively. The total number of incident K^+ mesons was $\sim 10^6$, and the data were recorded on $\sim 4 * 10^5$ stereo-frames. In the fiducial volume of the bubble chamber, K^+ momentum varies from $\sim$ 730 MeV for entering kaons to zero for those that range out through ionization. Throughout this momentum interval, all collisions and decays of incident K^+ mesons are efficiently detected. The K^+ momentum at interaction point is determined from the spatial distance between the detected vertex and the center of the observed maximum due to decays of stopping K^+ mesons. Secondary protons and charged pions are identified by ionization, charged kaons — by ionization and decays, K^0_S mesons — by the ranges and emission angles of decay pions, and γ-quanta — by conversion to an e^+e^- pair. Charged particles are momentum-analyzed by range, and γ-quanta — by the summed length of the electron–positron shower. The apparatus efficiency for γ-quanta with $E_\gamma > 30$ MeV is close to 100%. Further details on the experimental procedure may be found in [14, 15, 8].

Radiative decays of the Θ^+ baryon were searched for among the collisions with one or more detected γ-quanta in the final state: $K^+\mathrm{Xe} \to K^+(m\gamma)X$ and $K^+\mathrm{Xe} \to K^0_S(m\gamma)X$, $K^0_S \to \pi^+\pi^-$, where $m \geq 1$. We scanned for and then analyzed the K^+Xe collisions that showed either a secondary K^+ or a Vee from $K^0_S \to \pi^+\pi^-$, plus at least one e^+e^- pair from γ conversion that pointed back to the primary vertex. The collisions involving $K^0_S \to \pi^+\pi^-$ were selected in the full data sample, and those with a secondary K^+ — in nearly 30% of the data. The events were selected in a double scan of the film, and a portion of the film was scanned three times for better understanding of the scanning efficiency. All selected events were then carefully measured and reconstructed in space using specially designed stereo-projectors. In the interval $350 < p(K^+) < 600$ MeV of the incident K^+ momentum, we found 3 events of the reaction $K^+\mathrm{Xe} \to K^0_S\gamma X$, $K^0_S \to \pi^+\pi^-$ and 11 events of the reaction $K^+\mathrm{Xe} \to K^+\gamma X$ with $E_\gamma > 30$ MeV. We also found 20 events of the reaction $K^+\mathrm{Xe} \to K^0_S X$ with $K^0_S \to \pi^+\pi^-\gamma$.

The dominant source of background for the radiative decays $\Theta^+ \to K^0p\gamma$ and $\Theta^+ \to K^+n\gamma$ are the radiative non-resonant transitions $K^+n \to K^0p\gamma$, $K^+n \to K^+n\gamma$, and $K^+p \to K^+p\gamma$. We estimate the probabilities of these transitions relative to corresponding binary reactions $K^+n \to K^0p$, $K^+n \to K^+n$, and $K^+p \to K^+p$ using the formalism developed in [16] (see also [12]). The cross-section ratios $\sigma(K^+n \to K^0p\gamma)/\sigma(K^+n \to K^0p)$, $\sigma(K^+n \to K^+n\gamma)/\sigma(K^+n \to K^+n)$, and $\sigma(K^+p \to K^+p\gamma)/\sigma(K^+p \to K^+p)$ increase with incident momentum $p(K^+)$ by a factor ~ 2 between the boundary values $p(K^+) = 350$ and 600 MeV. For our experimental conditions, the yields of the radiative

reactions $K^+n \to K^0p\gamma$, $K^+n \to K^+n\gamma$, and $K^+p \to K^+p\gamma$ relative to $K^+n \to K^0p$, $K^+n \to K^+n$, and $K^+p \to K^+p$ are computed as 3.8×10^{-4}, 5.6×10^{-4}, and 7.6×10^{-4}, respectively.

The experimental determination of the probabilities of radiative processes $K^+\mathrm{Xe} \to K^0_S\gamma X$ and $K^+\mathrm{Xe} \to K^+\gamma X$ relative to the charge-exchange and elastic reactions $K^+\mathrm{Xe} \to K^0_S X$ and $K^+\mathrm{Xe} \to K^+X$ relies on the scanning information for the total numbers of events with detected $K^0_S \to \pi^+\pi^-$ decays or secondary K^+ mesons. In the interval $350 < p(K^+) < 600$ MeV of the incident K^+ momentum, the scan found 12750 ± 750 events of the charge-exchange reaction with $K^0_S \to \pi^+\pi^-$. With three events of the radiative reaction $K^+\mathrm{Xe} \to K^0_S\gamma X$ detected with an efficiency $\epsilon(K^0_S\gamma X) = 0.65 \pm 0.06$, we obtain the relative probability

$$W(K^+\mathrm{Xe} \to K^0_S\gamma X)/W(K^+\mathrm{Xe} \to K^0_S X) = (3.6 \pm 2.1) \times 10^{-4}$$

which agrees with the theoretical prediction. When extracting the total number of events of the elastic reaction $K^+\mathrm{Xe} \to K^+X$ from the scanning information, the events due to coherent scattering $K^+\mathrm{Xe} \to K^+\mathrm{Xe}$ are rejected by the cut $T' < 0.9T$ where T and T' are kinetic energies of the incident and secondary kaons. The number of events of the elastic reaction corrected for the cut $T' < 0.9T$ is estimated as 29500 ± 2100 events for $350 < p(K^+) < 600$ MeV. With 11 events of the corresponding radiative reaction $K^+\mathrm{Xe} \to K^+\gamma X$ detected with an efficiency $\epsilon(K^+\gamma X) = 0.75 \pm 0.05$, we obtain the relative probability

$$W(K^+\mathrm{Xe} \to K^+\gamma X)/W(K^+\mathrm{Xe} \to K^+X) = (5.0 \pm 1.7) \times 10^{-4}.$$

The latter ratio is in fact the mean value of relative probabilities for the proton and neutron, because the numbers of elastic K^+p and K^+n collisions are expected to be virtually equal (the proportion between protons and neutrons in the Xenon nucleus proves to be very close to the inverse ratio between the K^+p and K^+n elastic cross sections [18, 19].) Again, the measured value agrees with the theoretical prediction of 6.6×10^{-4} (the mean value for the proton and neutron, see above). The number of detected charge-exchange events with $K^0_S \to \pi^+\pi^-\gamma$ (20 ± 5) agrees with the results of a simulation[2] that predicts 23 events of this type. We may conclude that the detected $K^+\mathrm{Xe} \to K^0_S\gamma X$

[2] The simulation reproduces the experimental conditions and selections, relies on the total number of detected events with $K^0_S \to \pi^+\pi^-$ decays for normalization, and accounts for the branching fraction of the decay $K^0_S \to \pi^+\pi^-\gamma$ [20].

and $K^+\mathrm{Xe} \to K^+\gamma X$ events are consistent with being entirely due to the non-resonant radiative transitions $K^+n \to K^0p\gamma$, $K^+n \to K^+n\gamma$, and $K^+p \to K^+p\gamma$.

In estimating the probabilities of radiative decays $\Theta^+ \to K^0p\gamma$ and $\Theta^+ \to K^+n\gamma$, we rely on our previous observation of 71.7 ± 13.2 decays $\Theta^+ \to K^0p$, $K^0_S \to \pi^+\pi^-$ in the K^+ momentum range of 445–525 MeV [9]. Correcting for the scanning efficiency of 0.83 for the reaction $K^+\mathrm{Xe} \to K^0_S X$ and for unmeasurable events whose fraction reaches 0.40 ± 0.07, we obtain a "reference" signal of

$$N_0(\Theta^+ \to K^0p,\ K^0_S \to \pi^+\pi^-) = (145 \pm 27) \text{ events}$$

for $445 < p(K^+) < 525$ MeV. To derive the "reference" number of $\Theta^+ \to K^+n$ decays, we assume equal branching fractions for $\Theta^+ \to K^0p$ and $\Theta^+ \to K^+n$, correct for the probability of $K^0 \to \pi^+\pi^-$ and for the difference of detection efficiencies for events with secondary K^+ and $K^0_S \to \pi^+\pi^-$, and take into account that the final state $K^+p\gamma$ has been analyzed for only 30% of the data. Thereby, for $445 < p(K^+) < 525$ MeV we obtain

$$N_0(\Theta^+ \to K^+n) = (127 \pm 23) \text{ events.}$$

Of the three detected events of the reaction $K^+\mathrm{Xe} \to K^0_S\gamma X$, only one lies within the interval 445–525 MeV of incident K^+ momentum. The background from the the non-resonant radiative transition $K^+n \to K^0p\gamma$ is estimated as 1.0 events. The final state of the observed event is $K^0_Sp\gamma$ as expected for $\Theta^+ \to K^0p\gamma$, but the effective mass of this three-body system ($m_3 = (1515 \pm 12)$ MeV) is below $m(\Theta^+) = (1538 \pm 2)$ MeV [9] by almost 2σ. Therefore, we disregard this event and conclude that the number of detected $\Theta^+ \to K^0p$ decays is less than 2.3 at 90% confidence level. Dividing by the detection efficiency $\epsilon(K^0_S\gamma X)$ and by the reference signal $N_0(\Theta^+ \to K^0p,\ K^0_S \to \pi^+\pi^-)$ as quoted above, we obtain

$$\Gamma(\Theta^+ \to K^0p\gamma)/\Gamma(\Theta^+ \to K^0p) < 0.032 \text{ at 90\% confidence level.}$$

Of the 11 detected events of the reaction $K^+\mathrm{Xe} \to K^+\gamma X$, three fall within the incident momentum interval of $445 < p(K^+) < 525$ MeV (two events are at $350 < p(K^+) < 445$ MeV and six — at $525 < p(K^+) < 600$ MeV). The background from non-resonant transitions $K^+N \to K^+N\gamma$ is estimated as 4.7 events, so the number of detected $\Theta^+ \to K^+n$ decays is less than 3.0 at 90% confidence level [21]. Dividing by the detection efficiency $\epsilon(K^+\gamma X)$ and by the corresponding reference signal $N_0(\Theta^+ \to K^+n)$, we obtain

$$\Gamma(\Theta^+ \to K^+n\gamma)/\Gamma(\Theta^+ \to K^+n) < 0.041 \text{ at 90\% confidence level.}$$

Substituting $\Gamma(\Theta^+ \to K^0p) = \Gamma(\Theta^+ \to K^+n) = (0.19 \pm 0.05)$ MeV as measured in [9], we are able to restrict the absolute partial widths of Θ^+ radiative decays: $\Gamma(\Theta^+ \to K^0p\gamma) < 8$ keV and $\Gamma(\Theta^+ \to K^+n\gamma) < 11$ keV at 90% confidence level. These measurements

are in obvious disagreement with the "optimistic" predictions $\Gamma(\Theta^+ \to K^0 p\gamma) = 8$–$10$ keV and $\Gamma(\Theta^+ \to K^+ n\gamma) = 34$–$41$ keV [10]. On the other hand, the sensitivity of our experiment is insufficient for a substantiative comparison with lower predictions [11, 12].

Apart from the radiative reactions $K^+\mathrm{Xe} \to K^0_S\gamma X$ and $K^+\mathrm{Xe} \to K^+\gamma X$, we have also searched for the inelastic collisions involving formation of neutral pions. In the interval $540 < p(K^+) < 660$ MeV of the incident K^+ momentum, 22 events of the reaction $K^+\mathrm{Xe} \to K^0_S\pi^0 X$, $K^0_S \to \pi^+\pi^-$ and 27 events of the reaction $K^+\mathrm{Xe} \to K^+\pi^0 X$ have been found. The distribution of these inelasic events in incident K^+ momentum steeply increases with $p(K^+)$ from the threshold of $p(K^+) \simeq 520$ MeV to the maximum measured value of $p(K^+) = 660$ MeV. The energy spectrum of detected π^0 mesons agrees with that for the simulated reaction $K^+N \to KN\pi^0$ on a bound nucleon [22]. Selecting the beam-momentum interval $600 < p(K^+) < 660$ MeV with $\langle p(K^+)\rangle \simeq 640$ MeV and taking into account the total numbers of events due to the charge-exchange and elastic reactions $K^+\mathrm{Xe} \to K^0_S X$ and $K^+\mathrm{Xe} \to K^+ X$ (not quoted), for the reactions with π^0 emission on the Xenon nucleus we obtain $W(K^+\mathrm{Xe} \to K^0_S\pi^0 X)/W(K^+\mathrm{Xe} \to K^0_S X) = (0.90 \pm 0.23)\%$ and $W(K^+\mathrm{Xe} \to K^+\pi^0 X)/W(K^+\mathrm{Xe} \to K^+ X) = (0.31 \pm 0.07)\%$ at $p(K^+) = 640$ MeV. These relative yields have been corrected for the scanning efficiency for the reactions of π^0 emission and for π^0 absorption in the Xenon nucleus [23]. Substituting the measured cross sections of the binary reactions at $p(K^+) = 640$ MeV as $\sigma(K^+n \to K^0 p) = (7.5 \pm 0.5)$ mb, $\sigma(K^+n \to K^+n) = (8 \pm 1)$ mb, and $\sigma(K^+p \to K^+p) = (12.5 \pm 1.0)$ mb [17, 18, 19] and taking into account that the Xe nucleus consists of $Z = 54$ protons and $A - Z = 77$ neutrons, we obtain

$$\sigma(K^+n \to K^0 p\pi^0) = (68 \pm 18)\ \mu\mathrm{b},$$
$$\sigma(K^+N \to K^+N\pi^0) = (30 \pm 8)\ \mu\mathrm{b},$$

where the latter refers to the cross section averaged over constituent nucleons of the Xe nucleus. The cross sections of these reactions for $p(K^+) \simeq 640$ MeV were previously measured in a single experiment that used a deuterium bubble chamber [24]: $\sigma(K^+n \to K^0 p\pi^0) = (80 \pm 20)\ \mu$b, $\sigma(K^+d \to K^+\pi^0 pn) = (0 \pm 20)\ \mu$b. The former value is in good agreement with our measurement.

In summary, we have analyzed the data on the reactions $K^+\mathrm{Xe} \to K^0\gamma X$ and $K^+\mathrm{Xe} \to K^+\gamma X$, obtained with the bubble chamber DIANA, for possible radiative decays of the $\Theta^+(1540)$ baryon: $\Theta^+ \to K^0 p\gamma$ and $\Theta^+ \to K^+ n\gamma$. No signals have been observed, and we derive the upper limits $\Gamma(\Theta^+ \to K^0 p\gamma)/\Gamma(\Theta^+ \to K^0 p) < 0.032$ and $\Gamma(\Theta^+ \to K^+ n\gamma)/\Gamma(\Theta^+ \to K^+ n) < 0.041$ which, upon using our previous measurement

of $\Gamma(\Theta^+ \to KN)$, translate to $\Gamma(\Theta^+ \to K^0 p\gamma) < 8$ keV and $\Gamma(\Theta^+ \to K^+ n\gamma) < 11$ keV at 90% confidence level. We have also measured the cross sections of K^+-induced reactions involving emission of a neutral pion: $\sigma(K^+ n \to K^0 p\pi^0) = (68 \pm 18)$ μb and $\sigma(K^+ N \to K^+ N\pi^0) = (30 \pm 8)$ μb for incident K^+ momentum of 640 MeV.

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